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VIDEO DIGITAL FILTER STUDY II: temporal first-order recursive digital filter

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VIDEO DIGITAL FILTER STUDY II: TEMPORAL FIRST-ORDER RECURSIVE DIGITAL FILTER

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Summary

A study is being made of methods of reducing the level of noise in television picture signals.

This Report describes a low-pass filter that acts in the temporal-frequency domain whilst allowing full spatial-frequency resolution on stationary scenes.

The filter was built in a digital first-order recursive form. It works with 8-bit monochrome p.c.m. signals at a 13·3 MHz sample rate.

Using the filter, noise was significantly reduced and, for stationary pictures full spatial-frequency resolution was retained. Moving objects were, however, smeared and some form of adaptive filter employing movement detection is considered desirable.

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TEMPORAL FIRST-ORDER RECURSIVE DIGITAL FILTER

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VIDEO DIGITAL FILTER STUDY II:
TEMPORAL FIRST-ORDER RECURSIVE DIGITAL FILTER

N.E. Tanton, B.A.

1. Introduction

A study of filtering methods is in progress with the aim of reducing the levels of unwanted signals accompanying a video signal, such as random noise and those due to film grain, without impairing picture quality.

It is known that there are both spatial and temporal frequencies at which the human eye shows maximum sensitivity.[1] In the spatial domain the peak occurs at frequencies of around 2 cycles per degree,* whilst in the temporal domain the peak is at about 7 Hz. Noise on a television picture is generally well distributed in the spatial and temporal frequency domains but is most objectionable at those frequencies corresponding to the peaks of the eye's response. One way of reducing the visibility of noise, therefore, is to attenuate spatial- or temporal-frequency components in the vicinity of these peaks.

Low-pass filtering in the spatial-frequency domain has been described in another Report,[2] in which both horizontal and vertical spatial filters are considered. However, filtering of this form which is sufficient to produce a significant attenuation for spatial-frequencies around the response-peak of the eye's acuity characteristic (and hence to produce a noticeable reduction in noise visibility) results in an unacceptable loss of picture detail.

This Report describes a low-pass digital filter which acts in the temporal-frequency domain whilst allowing the display of stationary scenes with full spatial resolution. Moving objects are, however, smeared, filtering causes picture defects similar to those seen when using a long-persistence cathode-ray display tube. The filter is of the first-order recursive form[2] and has a time-constant that can be easily varied. Thus the filter could later be made adaptive (a facility which could prove necessary if movement portrayal is not to be degraded).

2. Theory

A first-order recursive filter is shown in Fig. 1. If it is to work in the temporal domain the delay τ_p should be one picture period, i.e. 40 ms for System I.

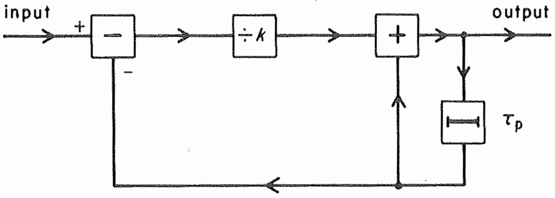

Fig. 1 - Basic first-order recursive temporal filter

The filtering operation has already been described fully,[2] but a brief resumé outlining temporal filtering follows. The filter input at any instant is a signal corresponding to a particular picture element of the scanned scene, and this is compared with the filter output delayed by exactly one picture period. With a noise-free monochrome picture of a stationary object there is zero inter-picture difference signal and the filter output is equal to its input. If, however, some perturbation (such as noise or a signal due to film grain) gives rise to a finite difference between signals from the same picture element on consecutive pictures, this difference is divided by the 'kernel' k and added to the output produced one picture-period earlier as a (small) modification.

The impulse response of the filter is a decreasing exponential characteristic (as with a long persistence display-tube phosphor), the time constant τ depending on the value of k such that

$$\tau = \sqrt{k(k-1)} \,.\, \tau_p \qquad (1)$$

where τ_p = the picture period.
The value of τ is given in Table 1 for various values of k.

TABLE 1

k	τ (seconds)	τ (picture periods)
2	0·057	1·4
4	0·14	3·5
8	0·30	7·5
16	0·62	15·5

At any instant the filter is processing signals derived from corresponding picture elements in successive pictures. With a purely temporal filter a moving object is spatially filtered because a single point in the object no longer corresponds to the same picture element in succeeding pictures, movement therefore results in reduced spatial resolution of the moving object. Another way of looking at this is to consider each displayed picture element as having an exponential decay characteristic, which results in a 'smearing' of moving objects. However, no spatial filtering takes place for stationary objects within the picture. Appendix A describes the process of temporally filtering a scene containing movement.

The amplitude component of the temporal-frequency characteristic of the filter of Fig. 1 is

$$|H(f)| = \left\{1 + 2k(k-1)(1 - \cos 2\pi f\tau_p)\right\}^{-\frac{1}{2}} \qquad (2)$$

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* Corresponding to vertical bars of about 0·5 MHz on a 625-line/50 field per second television display viewed at a distance of five times picture height.

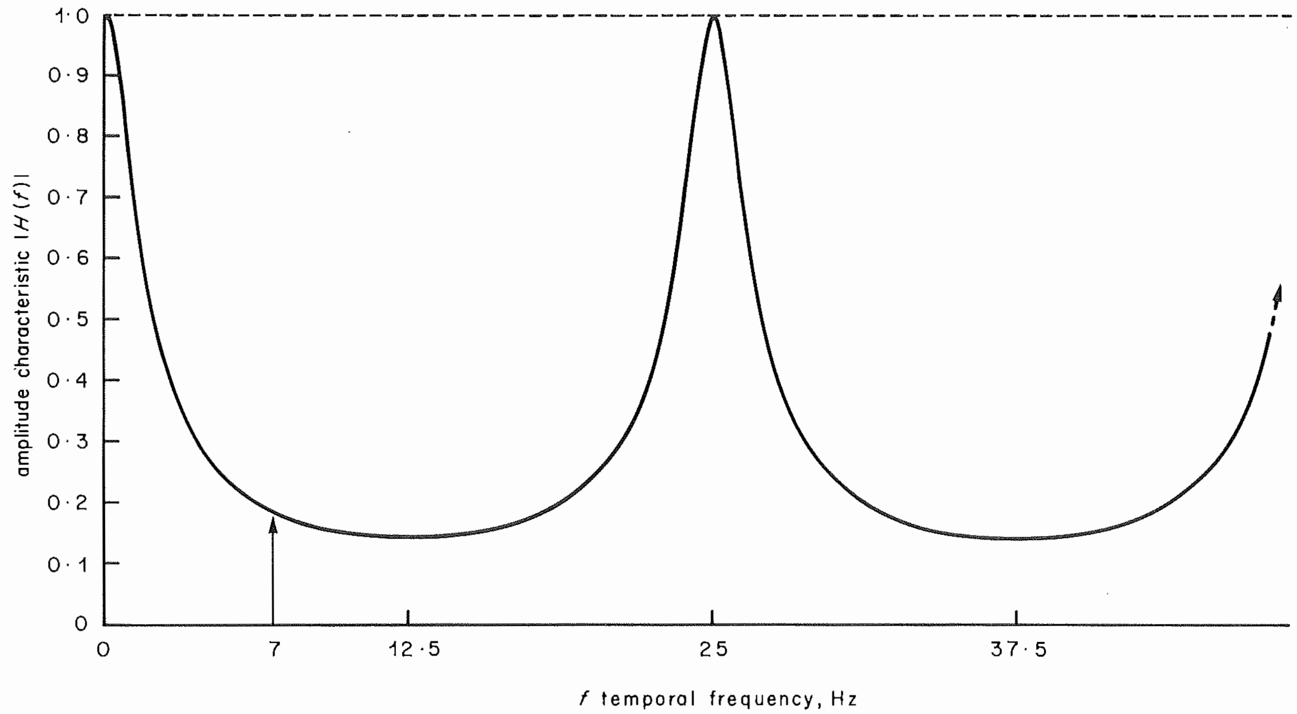

Fig. 2 - Amplitude characteristic of the first-order recursive filter of Fig. 1 with τ_p equal to 40 msec and k equal to 4

where τ_p = 0·04 seconds. The characteristic is therefore periodic in the temporal-frequency domain at intervals of 25 Hz and Fig. 2 shows the characteristic for k equal to 4. The figure also shows the appropriate position of the peak of the temporal characteristic of the human eye and indicates that the filter provides a significant attenuation at this frequency (14·7 dB for k = 4 at 7 Hz).

The noise-power reduction produced by a first-order recursive filter with a kernel k is

$$R = 10 \log_{10}(2k - 1)\text{dB} \qquad (3)$$

and is shown in Table 2 for various values of k.

TABLE 2

Maximum Attenuation and Noise-Power Reduction

k	absolute noise-power reduction R	maximum attenuation at odd multiples of f = 12·5 Hz
2	4·8 dB	9·5 dB
4	8·5 dB	16·9 dB
8	11·8 dB	23·5 dB
16	14·9 dB	29·8 dB

It must be emphasised that the values of R in Table 2 are unweighted noise-reductions. Subjective noise-weighting for a temporal filter would also take into account the temporal characteristics of the eye/brain combination.

3. Filter realisation

Analogue recursive filters are impractical since noise inherent in the filter delay-element recirculates and the temporal filter is therefore best built in digital form. For instrumental reasons the sampling frequency used for digitally coding the input signal was chosen to be locked to a multiple of television line frequency (in this case 851 times line frequency).

The total amount of storage required for the delay partly depends on the level of filtering to be applied. Reference 2, which deals with spatial filtering, explains how extra bits are required in the processing loop of the filter to maintain correct signal reproduction. If extra bits (in addition to those describing the input and output signals) are not added, inter-sample differences, which are shifted by division to lower levels of significance, are not preserved for subsequent processing. Specifically, if the kernel k is conveniently restricted to values of k equal to 2^n (where n is an integer), n extra bits are required in the processing loop. Ideally, for an 8-bit p.c.m. input signal, $8{+}n$ bits must therefore be stored in the recursive delay for each input word.

The number of words to be stored is governed by the sample rate. However, as it is necessary to store words corresponding to only the active picture area, storage sufficient for 397325 words is required with a 13·29 MHz (851 times line frequency) word rate (with 691 elements per active line and 575 active lines per picture).

For this investigation a 'partial' picture store consisting of a 16,384 x 24 bit core-store with an access time of about 800 ns was used. Thus it was possible to process

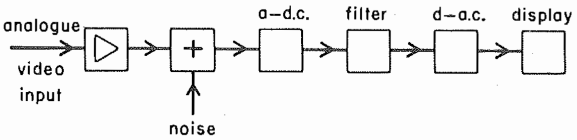

Fig. 3 - Experimental arrangement for filter study

only one-ninth of the active picture area using 8-bit words (i.e. no extra bits in the loop). In order to handle a 13·29 MHz input word-rate the signals corresponding to one-ninth of the active picture area were temporarily stored in a buffer (fast read-in, slow read-out), the 8-bit words being then reassembled in groups of 3 words and passed relatively slowly into the core-store.

Two consequences of the limited storeage were as follows. First, the surrounding 8/9th of the picture was unprocessed thereby enabling direct comparisons to be made between filtered and unfiltered picture areas, and secondly, as no extra loop bits were used a 'dead-band' effect occurred for all values of k greater than unity. This was because, with insufficient bits in the loop a 'paralysis' can occur in which signal-differences smaller than an amplitude corresponding to one $(8-n)$th significant bit become 'locked-in' to the processing loop and only disappear when overwritten by signal differences, or noise pulses, of greater amplitude. The paralysis was barely perceptible for practical levels of filtering except on 'fade-to-black' type shot-changes where a low-level ghost of the previous picture was faintly visible until overwritten by noise or fresh picture information.

The properties of the filter were investigated using the apparatus indicated in Fig. 3. White noise was added to the analogue video signal.

4. Results

In order to investigate the reduction in visibility of noise, a picture consisting of uniform grey was used and the noise was added with an r.m.s. amplitude corresponding to the third most significant bit.

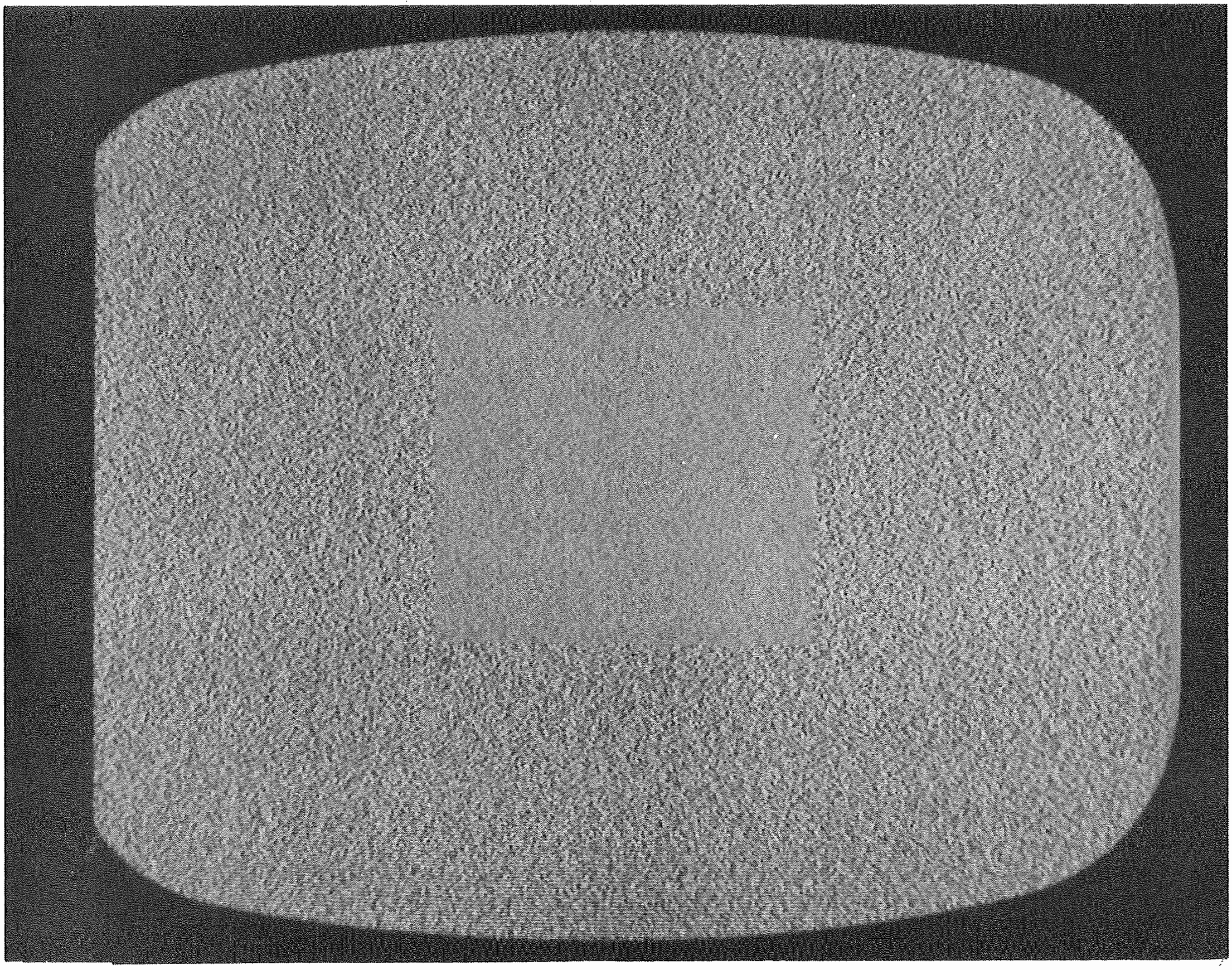

Fig. 4 - Noise reduction of field of grey, k equal to 4

Central picture area processed, surrounding area unprocessed (exposure time one picture period)

Fig. 4 shows a photograph (exposure one picture period) of the uniform grey picture when the signal was processed with k equal to four; the signals corresponding to the central portion were processed, those describing the surround were not. The absolute noise-power reduction for k equals four is 8·5 dB (Table 2). The subjective noise-reduction is less than this value since the effect of the eye/brain combination on the modified temporal characteristic of the noise has not been taken into account. The visibility of the white noise is nevertheless reduced significantly. Subjectively, the filtered noise appears like shifting sand, the filtering modifying the temporal- (but not spatial) frequency spectrum, and the apparent speed of the 'shifting' is dependent on the amount of filtering.

The perceived luminance of the processed picture is slightly less than that of the unprocessed picture because of the influence of the display tube gamma on the noise perturbations.

To demonstrate the full spatial resolution of the filtered pictures for stationary scenes, the effect of the filter on a test-card is shown in Fig. 5; the noise level used was the same as that used for Fig. 4 and the filtered area is outlined. A kernel k equal to 4 was again used. The filtered area includes some of the test-card frequency bars, in order to show that spatial resolution (in this case horizontal) was not impaired.

As has been explained in Section 2, moving objects within a temporally-filtered scene lose spatial resolution. Fig. 6 shows the picture obtained when a cylinder of fairly coarse frequency-bars was rotated at constant speed in front of the camera providing the signal to be filtered. At the particular rotational velocity used, the moving bars in the centre of the filtered portion of Fig. 6 represent a temporal frequency of about 2·5 Hz. The central portion of the picture was filtered with k = 4 and the photographic exposure was one picture period.

With only 8 bits of storage capacity in the recursive loop some 'dead-band' effect is to be expected, as discussed in Section 3. No perceivable paralysis results from small amounts of filtering (k = 2 or 4, for instance) but the effect

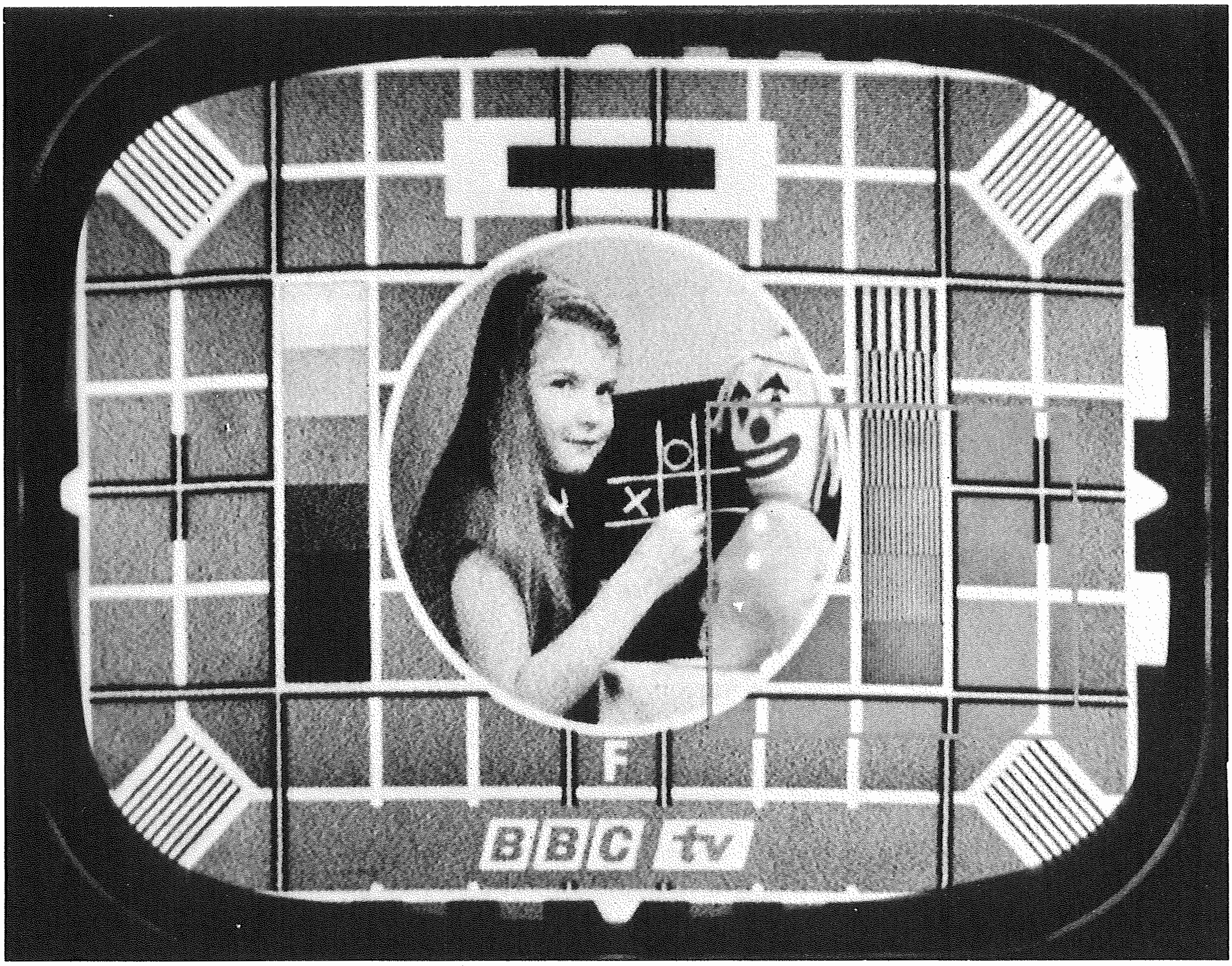

Fig. 5 - Noise reduction on a stationary picture
(Test-card F) showing full spatial resolution (processed area outlined), k equal to 4 (1 picture period exposure time)

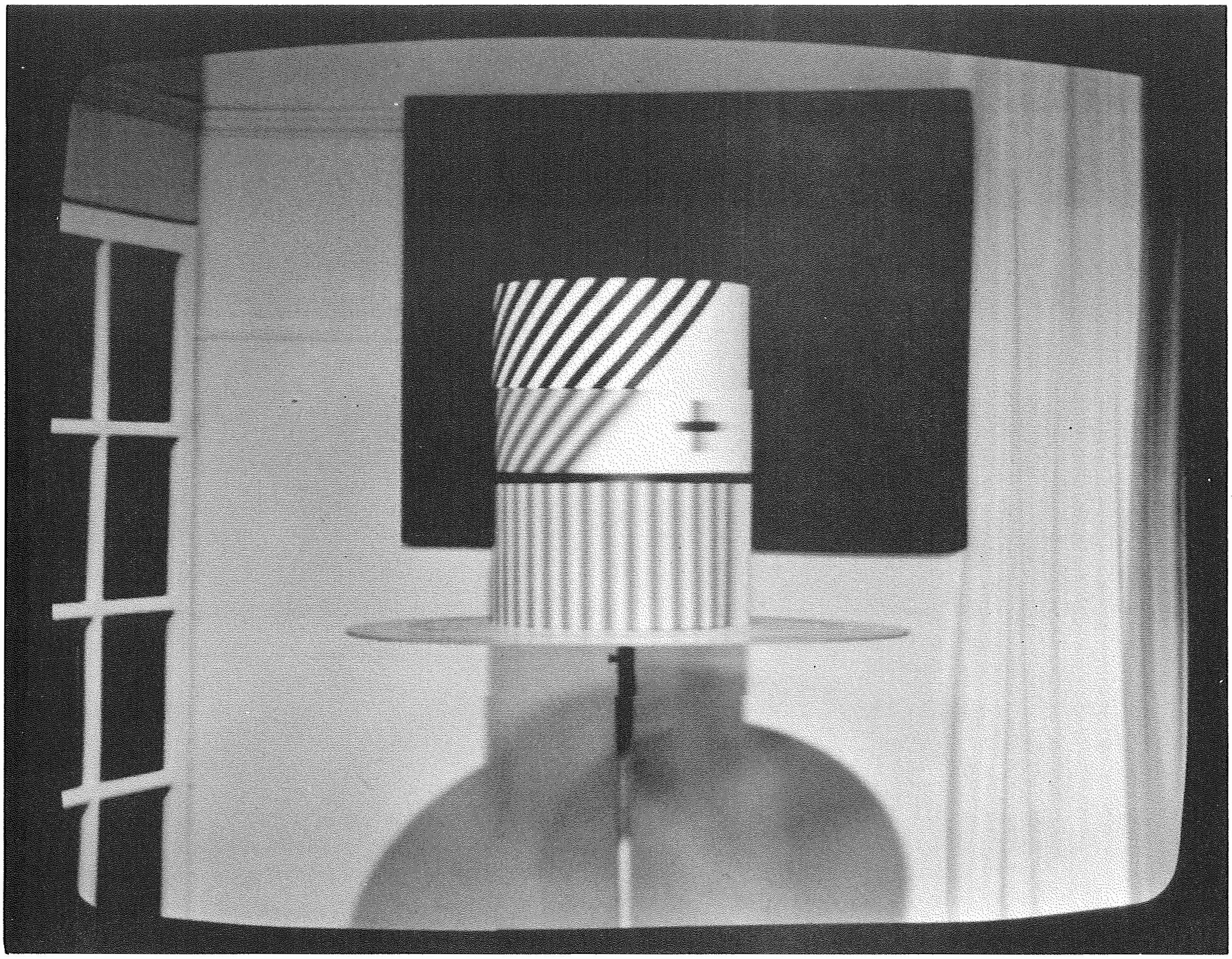

Fig. 6 - Movement portrayal on frequency bars moving from right to left showing loss of spatial resolution in processed area, k equal to 4. Middle moving vertical bars represent 2·5 Hz temporal frequency. (1 picture period exposure time)

is none the less present even at the level of filtering shown in Fig. 6 (k = 4).

However, at high levels of filtering the effect becomes visible as shown in Fig. 7. Here picture information was 'locked' into the filter and could only be overwritten by subsequent high-level interpicture differences. In the test illustrated by Fig. 7 a field of grey replaced test-card F whilst the latter was being heavily filtered (k = 64) with insufficient bits in the recursive loop. A low-level remnant of the test card was thus 'frozen in' and would remain unchanged unless overwritten by noise or other difference signals of sufficient amplitude. The photograph in Fig. 7 was taken about 20 seconds after the change to grey was made. If enough extra bits (n = 6 corresponding to k = 64) had been available in the loop, the central, filtered portion of the test card would have decayed to an imperceptible level in 20 seconds; for k equal to 64 the filter time constant is 2·54 seconds.

If however a very noisy picture is heavily filtered the noise can give rise to interpicture signal-differences larger than the 'dead-band' region. In this case the paralysis is overcome by the noise and a low-level remnant such as that shown in Fig. 7 would decay in a relatively short time. This particular consequence of insufficient storage is therefore less noticeable on very noisy signals. Heavier filtering is thus possible with a modest amount of storage when processing very noisy signals.

However, the 'dead-band effect' causes only high amplitude noise to appear at the output, and this alters the visible nature of the noise; speckled isolated noise pulses replace a general 'sea' of noise, and may therefore be more noticeable.

5. Discussion of results

The temporal filter described significantly reduces the visibility of noise on television pictures, when very moderate amounts of filtering are applied. This can be seen in Figs. 4 and 5. On stationary scenes the temporal filtering imposes no loss of spatial resolution.

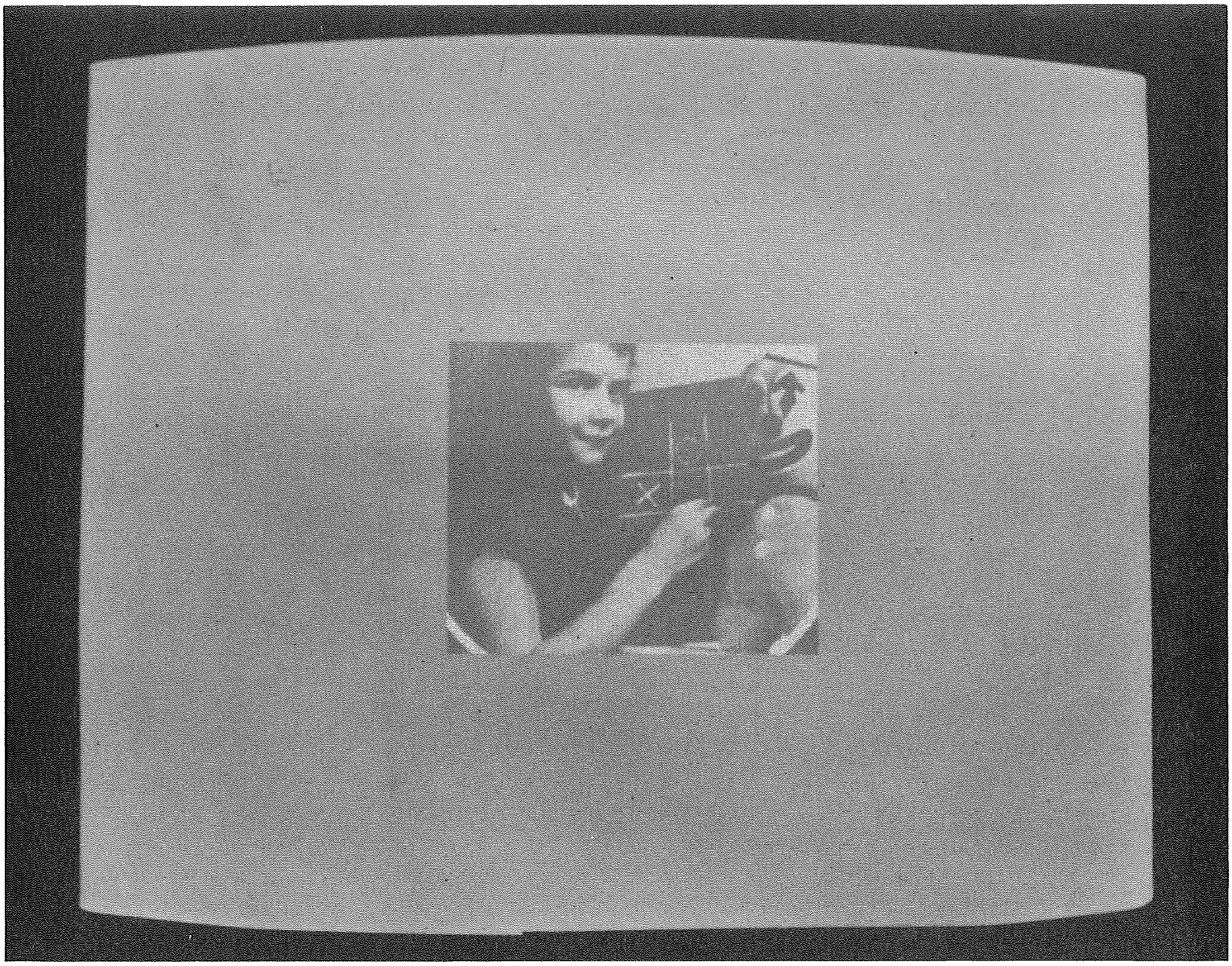

Fig. 7 - 'Deadband' effect of insufficient storage bits in recursive loop. Test-card F 'locked-in', exposure taken 20 seconds after cut-to-grey (exposure time 1 picture period), k = 64

If, however, a changing scene is depicted, temporal filtering produces a loss of spatial resolution of the moving object. This results in the unacceptable smearing visible in Fig. 6. Now it may be reasonable to expect the visibility of noise on moving objects within a picture to be less than that of noise in stationary areas, since the movement may distract the viewer's eye from the noise. If this is true the filter could be switched off or the filter kernel factor (k) reduced in magnitude for signals corresponding to those portions of the picture that are changing. The smearing of movement would be avoided, whilst noise in stationary areas would be reduced by heavy filtering. Work is in progress to investigate suitable methods of movement detection which could permit the level of filtering to be varied automatically.

6. Conclusions

A temporal filter has been developed which succeeds in reducing the visibility of noise on television pictures by a significant amount. Moving objects suffer from a smearing of detail, but it may be feasible to apply movement detection to make the filter adaptive and thereby to overcome movement portrayal problems.

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7. References

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2. DREWERY, J.O. 1974. Video digital filter study I – first-order recursive form. BBC Research Department Report No. 1975/3.

Appendix A

The Spatial Effects of a Temporal Filter Characteristic

Consider a two-dimensional image whose luminance amplitude is described by the function $E(x, y)$. This image-function can be described in terms of horizontal and vertical spatial frequencies m and n as

$$E(x, y) = \sum_m \sum_n A_{mn} \exp 2\pi \mathrm{j} \left\{ \frac{mx}{2a} + \frac{ny}{2b} \right\} \qquad (1)$$

where $2a$ is the picture width, $2b$ is the picture height and the Fourier coefficients A_{mn} constitute the two-dimensional spatial spectrum. If the image moves with horizontal velocity u and vertical velocity v then

$$E(x, y, t) = E(x - ut, y - vt) \qquad (2)$$

$$= \sum_m \sum_n A_{mn} \exp 2\pi \mathrm{j} \left\{ \frac{mx}{2a} + \frac{ny}{2b} - \left\{ \frac{mu}{2a} + \frac{nv}{2b} \right\} t \right\} \qquad (3)$$

Now

$$\frac{mu}{2a} + \frac{nv}{2b} = -f_{mn} \qquad (4)$$

where f_{mn} is the frequency at which crests of the spatial frequency (m, n) pass a fixed point in the image-plane. Then

$$E(x, y, t) = \sum_m \sum_n A_{mn} \exp 2\pi \mathrm{j} \left\{ \frac{mx}{2a} + \frac{ny}{2b} \right\} . \exp(\mathrm{j}\, \omega_{mn}\, t) \qquad (5)$$

where

$$\omega_{mn} = 2\pi f_{mn} \qquad (6)$$

If a filter with a purely temporal frequency characteristic $H(\mathrm{j}\omega)$ is used to process the image, an output-image E' will be formed described by

$$E'(x, y, t) = \sum_m \sum_n A_{mn} \exp 2\pi \mathrm{j} \left\{ \frac{mx}{2a} + \frac{ny}{2b} \right\} . \exp(\mathrm{j}\, \omega_{mn}\, t) \,.\, H(\mathrm{j}\, \omega_{mn}) \qquad (7)$$

$$= \sum_m \sum_n A'_{mn} \,.\, \exp 2\pi \mathrm{j} \left(\frac{mx}{2a} + \frac{ny}{2b} \right) . \exp(\mathrm{j}\, \omega_{mn}\, t) \qquad (8)$$

where the modified Fourier coefficients A'_{mn} are given by

$$A'_{mn} = A_{mn} \,.\, H(\mathrm{j}\, \omega_{mn}) \qquad (9)$$

The image spatial-frequency spectrum is therefore modified by a spectral function which depends on the image velocity. If $H(0)$ is unity it follows from Equations (4) and (9) that the spectrum of a stationary image is unmodified.

Equation (4) describes a straight line in m - n space for a given image velocity u, v and temporal frequency. It follows then from Equation (9) that such lines in m - n space corresponding to different values of ω_{mn} are lines of constant attenuation and phase. Moreover the lines are perpendicular to the direction of the image velocity.

If we consider, for example, a phosphor or camera tube with an exponential decay having a transfer function

$$H(\mathrm{j}\omega) = (1 + \mathrm{j}\omega\tau)^{-1} \qquad (10)$$

the output image spectrum Fourier coefficients will be described by

$$A'_{mn} = A_{mn} \cdot (1 + \mathrm{j}\omega_{mn}\tau)^{-1} \qquad (11)$$

A temporal exponential decay has been transformed into a spatial exponential decay in the direction of motion. Movement will therefore result in a loss of spatial resolution as the coefficients of higher spatial frequency components are progressively reduced in magnitude.

If the filter acts on sampled signals the filter transfer function has the form $H\{\exp(\mathrm{j}\omega\tau)\}$, see Ref. 2. Such a transfer function is periodic in $f = {}^1/\tau$ and therefore the function which modifies the individual spatial Fourier coefficients is also periodic.

Under these conditions a given attenuation (or phase) is represented by a set of equi-spaced parallel lines in m - n space, described by Equations (4) and (9) for the given attenuation (or phase).

For example, unattenuated spatial frequencies m_1 and n_1 (for a filter with unity zero-frequency gain and with a period τ_p) will be those frequencies satisfying the equation

$$\frac{m_1 u}{2a} + \frac{n_1 v}{2b} = \frac{r}{\tau_p} \qquad (12)$$

where r is an integer.

The filter described in this Report is of this form.

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